National Weather Service
Office of Meteorology

Technical Procedures Bulletin

Subject: The North Atlantic Hurricane Wind Wave Forecasting System (NAH)

Series No. 478

June 16, 2003 **Science Division, Silver Spring, MD 20910**

THIS IS THE FIRST TPB ON THIS PRODUCT

This bulletin, prepared by Dr. Yung Y. Chao, Mr. Lawrence D. Burroughs, and Dr. Hendrik Tolman, describes a new wave model which is designed to predict wind waves generated by hurricanes in the Western North Atlantic Ocean. This model uses the same 0.25° x 0.25° grid as the Western North Atlantic wave model (WNA) and the same computational and physics schemes as the NOAA WAVEWATCH III model. The NAH uses a blend of model wind outputs from the Geophysical Fluid Dynamics Laboratory (GFDL) Hurricane Model runs for each hurricane being followed and the Global Forecast System (GFS).

The NAH was implemented during the summer of 2001. Output from the model is available to the forecast community on a dedicated line to the Tropical Weather Center/National Hurricane Center, over the Satellite Broadcast to AWIPS, and on NAWIPS.

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The North Atlantic Hurricane Wind Wave Forecasting System (NAH)[1]

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1. Introduction

The present NCEP operational wave model for predicting global and regional ocean wind waves, NOAA WAVEWATCH III (NWW3) (Tolman 2002), uses wind data derived from the Global Forecast System (GFS, Kanamitsu *et al* 1991; Caplan *et al* 1997). It is well known that the details of highly intense and rapidly varying nature of the wind field associated with a tropical cyclone is poorly resolved by the GFS because its grid isn't fine enough. As a result, predicted wave conditions in areas under the influence of tropical storms usually are under predicted when GFS winds are used. Also, predicted directions and arrival times of swells in coastal areas tend to be inaccurate.

In order to provide a more accurate forecast of the storm track, intensity, and wind distribution, NCEP uses a separate model to generate the hurricane wind structure. This model, developed by the Geophysical Fluid Dynamics Laboratory (GFDL), is called the multiply nested movable mesh hurricane model (*e.g.,* Kurihara and Bender 1980; Kurihara *et al* 1990, 1995, and 1998) and is used during the hurricane season to produce forecast guidance for the National Hurricane Center. The model, however, considers only one storm at a time. When multiple storms exist simultaneously, a frequent event, one storm is considered at a time with the fine inner mesh grid, while the others are dealt with in the course outer mesh only. The details of their wind field structures are again not adequately described. Consequently, the combined effects of various wind fields associated with multiple storms on ocean waves cannot be adequately predicted by using a single run of the GFDL model. Therefore, the GFDL must be run for each storm currently occurring, so the detailed wind field structure of each storm can be captured. Furthermore, since the hurricane model uses a movable grid system, the domain for each model run does not necessarily cover the entire wave model domain. The problem is how to incorporate the wind fields from the various runs of the GFDL model with the background wind field of the GFS, to produce the most realistic wave field.

A procedure for unifying the wind from the GFS and that from the GFDL model for single or multiple storms has been developed. The procedure has been used to predict hurricane associated wind waves over the North Atlantic Ocean during the 2000 hurricane season from September through October. In what follows we will describe the procedure for predicting hurricane winds and waves, show the results of validation against observations, and present available products and planned dissemination routes for the hurricane season.

2. Hurricane Wind Field Specification for Wave Forecasting

The present operational GFDL hurricane model produces output data for the outer and inner mesh

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[1] OMB Contribution No. 198

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4 cycles per day at hourly intervals up to 78 hours. The outer mesh has a grid resolution of 1/3 by 1/3 degree covering an area of 75 by 75 degrees in latitude and longitude. The inner mesh has a grid resolution of 1/6 by 1/6 degree covering an area of 11 by 11 degrees. The center of the inner mesh is coincided with the center of the storm (the location of the lowest pressure). The operational GFS model provides output 4 cycles per day at 3-h intervals up to 168 hours. At this time we use the GFS winds from the 0000, 0600, 1200 and 1800 UTC cycles out to 78 hours. The first step is to interpolate lowest level wind data from GFS and GFDL grids at the same projection hour onto the North Atlantic Hurricane wave model (NAH) domain which is identical to the domain and grid resolution (0.25° x 0.25° lon/lat) of the Western North Atlantic wave model (WNA, Chao *et al* 2003) and adjust it to a height of 10 m. Since the GFDL hurricane model runs for each selected storm separately, discrepancies in the wind field features for the same storm from different model runs may occur if multiple storms co-exist. In order to resolve this problem, the concept of an area of influence (AOI) for each storm is introduced. Various definitions of AOI have been considered and tested. We have found that the following procedure provides the most realistic and consistent wind field structure:

(a) Determine the box area which has the shortest distance from the storm center to the 1015 MB isobar.

(b) Determine the box area which extends from the storm center to where the wind speed decreases to 7.5 m/s on each side of the box.

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(c) Form a new box area with each side taken from the side of these two boxes which has the smaller distance to the storm center.

(d) Restrict the new box area to be less or equal to a 12.5 degree and greater or equal to 3.5 degree longitude-latitude box.

(e) Replace the GFS winds in the AOI of each storm with GFDL winds.

(f) Use a weighted averaging procedure to have a smooth transition from one set of winds to the other in the vicinity of four boundaries of the AOI.

A detailed description regarding the specification of hurricane wind fields for wave prediction can be found in Chao and Tolman (2000). The NAH uses the blended wind fields as input to compute wave parameters.

3. Operational Procedure of Hurricane Wind-Wave Forecasting

The NAH is nearly identical to the WNA, a description of which can be found in Chao, Burroughs and Tolman (2003).The hurricane generated wind-wave forecasting procedure for the NAH is quite straightforward and is used during the entire hurricane season.

(a) Initialize the NAH at the official start of the hurricane season by initializing the wave field with output from the WNA and by using the winds from the GFS.

(b) Search for output from the GFDL model and continue running NAH at each model cycle for the duration of the hurricane season.

(c) Use procedure developed in section 2 above when GFDL output is available:
   (1) mean sea level pressure to determine storm center, and
   (2) the surface wind field in each AOI.

(d) Obtain output spectra from the NWW3 to furnish boundary wave conditions at the boundaries of the NAH domain at each computational step.

(e) Use GFS winds to continue the NAH operations when no tropical storms exist during the hurricane season.

4. Performance Evaluation

During September and October 2000, the procedures developed above were applied in a test mode. The system was run twice daily for the 0000Z and 1200Z UTC cycles. Figure 1 shows the tracks of all tropical storms that occurred during this period. The location of all available buoys is also given in the figure. Most of storm tracks are far away from buoys or storm strength is too weak to cause discernable wave height except Hurricane Gordon (officially named, September 14-18) and Helene (officially named, September 15-22). Figure 2.a shows the time series comparisons of measurements at Buoy No. 42036, which is located near the West Coast of Florida, and the NAH model predictions of the significant wave height, wind speed and wind direction interpolated to the buoy location from the surrounding grid point values. Similar time series for WNA model are given in Figure 2-b. The first peak in wave height in both figures appears near the 17th and 18th of September corresponds to Hurricane Gordon, while the second peak near the 22nd corresponds to Hurricane Helene. Figures 3.a and 3.b are similar time series plots for Buoy 42003 which is located in the deep water of the Gulf of Mexico. These figures indicate that the NAH (blended winds) provides more accurate prediction of waves than those of the WNA (GFS winds only).

Figure 4.a depicts the difference between the GFS wind field and the blended GFS and GFDL wind field for Hurricane Gordon. Immediately noticeable are the differences in scale and intensity of the wind fields. The resulting wave fields are also substantially different as shown in Fig. 4.b. Examples of wind and wave fields associated with hurricane Helene are shown in figures 5.a and 5.b. Here, the GFS wind field is somewhat lower than the blended wind field, but covers a much larger area than the blended wind field. This results in a larger field of high waves by using the GFS wind field than by using the blended wind field. Hurricane Helene tracked to the west of buoy 42036 in the Gulf of Mexico and showed the waves from Helene to be reasonably low at that location. The waves predicted at buoy 42036 by the WNA with the GFS wind field were too high, while those predicted by the NAH with the blended wind field were very close to the observed waves. The difference being due to the difference in aerial coverage of the two wave fields generated by the different wind inputs.

An important aspect in forecasting hurricane generated waves is the ability to provide information about swell conditions in coastal areas while one or more hurricanes are still far offshore. Many accidents occur near the coast where the weather is quite nice, yet dangerously high swells generated by hurricanes several hundred miles away begin to arrive. Figure 6.a shows the GFS and blended wind field pattern when hurricanes Isaac and Joyce co-exist during September 25 through October 1 in the far distance Atlantic Ocean from the East Coast. The blended wind field depicts the extent of the high winds of both hurricanes. This wind field results in a large front of long period waves well in front of the storms which will propagate to the East Coast area much faster than predicted by WNA (see Fig. 6b).

5. Products and Dissemination

The following wind and wave parameters will be available in GRIB format at:

ftp://polar.wwb.noaa.gov/pub/waves and

on AWIPS as GRIB bulletins (see Table 1):

- significant wave height,
- peak wave period and direction,
- wind speed and direction, and
- u- and v- wind components.

Spectral text bulletins are also available on the web at the site above and on AWIPS; see fig. 7 for a sample AWIPS bulletin and Table 2 for the locations and header information for each point where spectral output is available. The spectral text bulletins on the web and on AWIPS have different formats because of legacy constraints on AWIPS.

6. Concluding Remarks

An operational system for forecasting North Atlantic Hurricane wind waves and swells (NAH) using blended GFDL and GFS model winds has been developed, tested, and operated during the hurricane seasons of 2001 and 2002. Results of the validation study and the two preceding hurricane seasons show that the forecasting system provides more realistic hurricane wave predictions than those provided by the WNA which uses GFS winds only. The new system, in general, predicts much higher wave heights over the areas within hurricane influence and earlier arrival of longer and higher swells in coastal areas.

7. References

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Table1. WMO GRIB bulletin header descriptors.

T_1	T_2 [1]	A_1 [2]	A_2	dd	Station id
O	A B C J K M N P Y	O	A C E G I J K L M X N Y O	88	KWBJ

Where:
T_1 is the bulletin type descriptor: O - oceanographic
T_2 is the parameter descriptor, see notes
A_1 is the grid and domain descriptor: O - 0.25° x 0.25° lon./lat. grid over domain from 98.25°W - 29.75°W and 0.25°S - 50.25°N
A_2 is the forecast hour descriptor, see notes
dd is the surface descriptor: 88 - ocean surface

Notes:
1. Parameter descriptors:
   A - u-wind component
   B - v-wind component
   C - Total significant wave height
   J - Peak wave period
   K - Peak wave direction
   M - Peak wind sea period
   N - Peak wind sea direction
   P - D_m
   Y - T_m
2. Forecast hour descriptors at 6-h intervals from 0- to 72-h

Table 2. Name, location, and header information for spectral text bulletins associated with the NAH wave model.

Station Name	Position (N and W, except where indicated)		AWIPS and WMO Header
	Latitude	Longitude	
Points for Wave Spectra from the North Atlantic Hurricane (NAH) Regional Wave Model			
Northwest Atlantic Points			
44138	44.2	53.6	AGNT41 KWBJ OSBH01
44141	42.1	56.2	AGNT41 KWBJ OSBH02
44142	42.5	64.2	AGNT41 KWBJ OSBH03
44004	38.5	70.7	AGNT41 KWBJ OSBH04
44005	42.9	68.9	AGNT41 KWBJ OSBH05
44008	40.5	69.4	AGNT41 KWBJ OSBH06
44009	38.5	74.7	AGNT41 KWBJ OSBH07
44011	41.1	66.6	AGNT41 KWBJ OSBH08
44025	40.3	73.2	AGNT41 KWBJ OSBH09
OKX01	40.75	71.75	AGNT41 KWBJ OSBH10
Southeast Atlantic Points			
44014	36.6	74.8	AGNT42 KWBJ OSBH01
41001	34.7	72.7	AGNT42 KWBJ OSBH02
41002	32.3	75.2	AGNT42 KWBJ OSBH03
DSLN7	35.2	75.3	AGNT42 KWBJ OSBH04
41008	31.4	80.5	AGNT42 KWBJ OSBH05
41009	28.5	80.2	AGNT42 KWBJ OSBH06
41010	28.9	78.5	AGNT42 KWBJ OSBH07
Puerto_R_N	19.0	66.5	AGNT42 KWBJ OSBH08
ILM01	34.00	80.80	AGNT42 KWBJ OSBH09
ILM02	33.20	77.00	AGNT42 KWBJ OSBH10
JAX01	30.00	78.50	AGNT42 KWBJ OSBH11
41004	32.50	79.10	AGNT42 KWBJ OSBH12
CHS01	30.75	77.00	AGNT42 KWBJ OSBH13
TPC20	15.00	55.00	AGNT42 KWBJ OSBH14
TPC24	22.00	76.00	AGNT42 KWBJ OSBH15

Gulf of Mexico Points			
42001	25.9	89.7	AGGX44 KWBJ OSBH01
42002	25.9	93.6	AGGX44 KWBJ OSBH02
42003	25.9	85.9	AGGX44 KWBJ OSBH03
42007	30.1	88.8	AGGX44 KWBJ OSBH04
42019	27.9	95.0	AGGX44 KWBJ OSBH05
42020	27.0	95.5	AGGX44 KWBJ OSBH06
42035	29.2	94.4	AGGX44 KWBJ OSBH07
42036	28.3	84.4	AGGX44 KWBJ OSBH08
42039	28.5	86.0	AGGX44 KWBJ OSBH09
42040	29.2	88.2	AGGX44 KWBJ OSBH10
TPC25	24.00	80.00	AGGX44 KWBJ OSBH11
TPC26	23.00	86.00	AGGX44 KWBJ OSBH12
Caribbean Sea Points			
Puerto_R_S	17.5	66.5	AGCA42 KWBJ OSBH01
TPC21	15.00	63.00	AGCA42 KWBJ OSBH02
TPC22	12.00	77.00	AGCA42 KWBJ OSBH03
TPC23	15.00	80.00	AGCA42 KWBJ OSBH04

Notes:

1. The WMO/AWIPS headers follow the form given for oceanographic data, *i.e.*, $AGA_1A_2i_1i_2$, where i_1 is 4 and always means spectral wave data.

2. i_2 is the geographic location, where:

   0 - means Pacific Ocean, particularly in proximity to U.S. held islands (Hawaii and Guam's areas of responsibility)
   1 - means proximity to NE Atlantic States from Virginia northward
   2 - means proximity to SE Atlantic States from North Carolina southward and Puerto Rico
   4 - means proximity to southern Gulf of Mexico states
   6 - means proximity to Pacific States and southern British Columbia
   7 - means proximity to Panhandle of Alaska and northern British Columbia (Juneau's areas of responsibility)
   8 - means proximity to southern and southwestern Alaska (Anchorage's areas of responsibility)

3. A_1A_2 is used by the originating office (NCEP/NCO) to identify the oceanic area of the point, where:

   NT - Western Atlantic
   GX - Gulf of Mexico
   CA - Caribbean Sea
   PZ - Eastern Pacific
   GA - Gulf of Alaska
   PN - North Pacific including Bering Sea

AC - Arctic Ocean
HW - Hawaiian Waters
PW - Western Pacific
XT - Tropical Belt
PS - South Pacific

4. The AWIPS identifier form is NNNxxx: where NNN is OSB - Oceanographic Spectral Bulletin, and xxx takes the form: mnn - where m is the wave model and nn is the number of the point in a given geographic location according to note 2 above. nn can range from 01 - 99.

5. m is the wave model where:

   N is the NOAA WAVEWATCH III global wave model
   A is the Alaska Waters regional wave model
   W is the Western North Atlantic regional wave model
   H is the North Atlantic Hurricane regional wave model
   E is the Eastern North Pacific regional wave model
   P is the Eastern Pacific Hurricane regional wave model
   X is the Western North Pacific regional wave model
   T is the Western Pacific Typhoon regional wave model

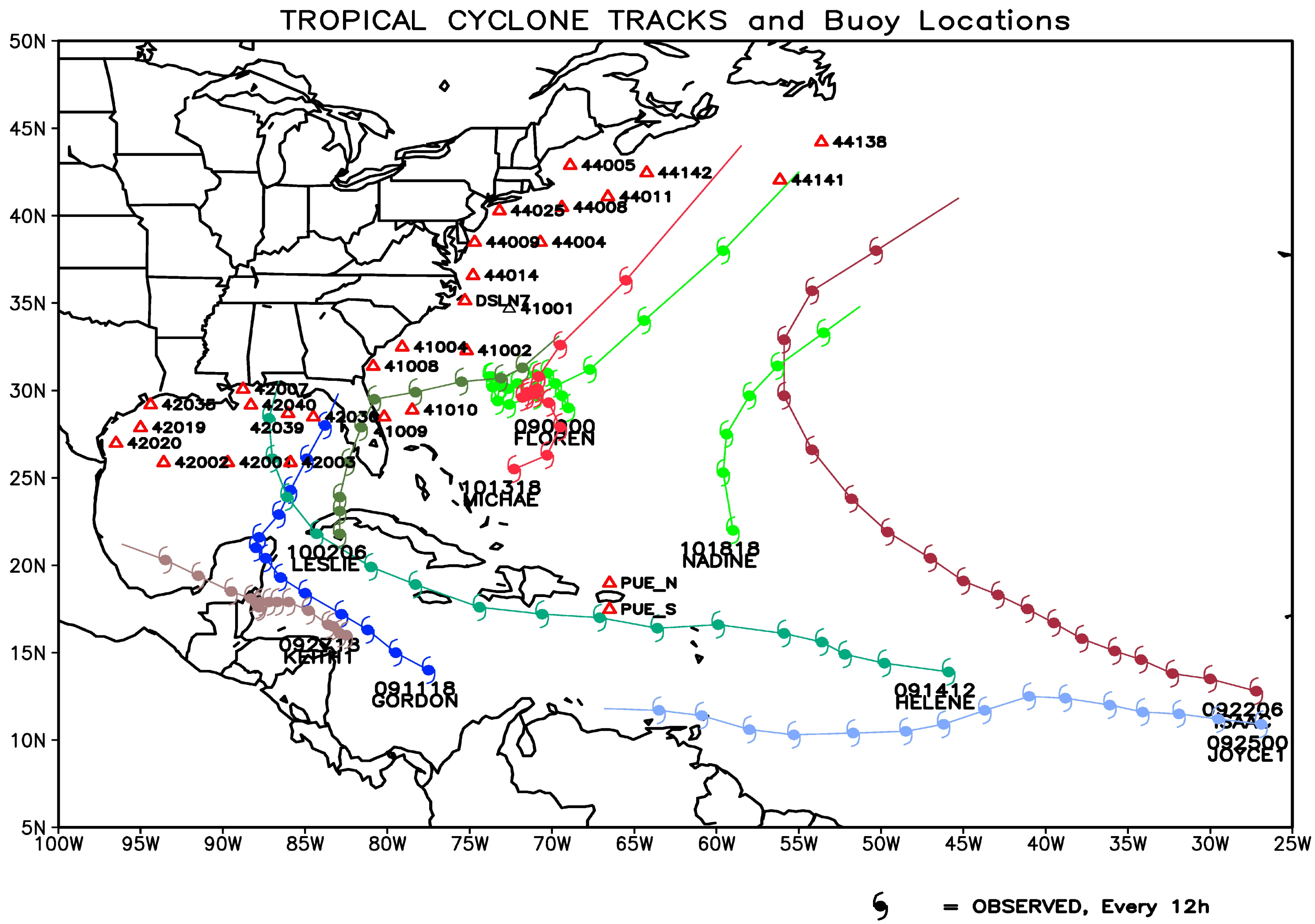

Figure 1. Hurricanes that occurred during September and October 2000 in the Western North Atlantic, Gulf of Mexico, and Caribbean Sea. Also shown are all the buoy positions in the area.

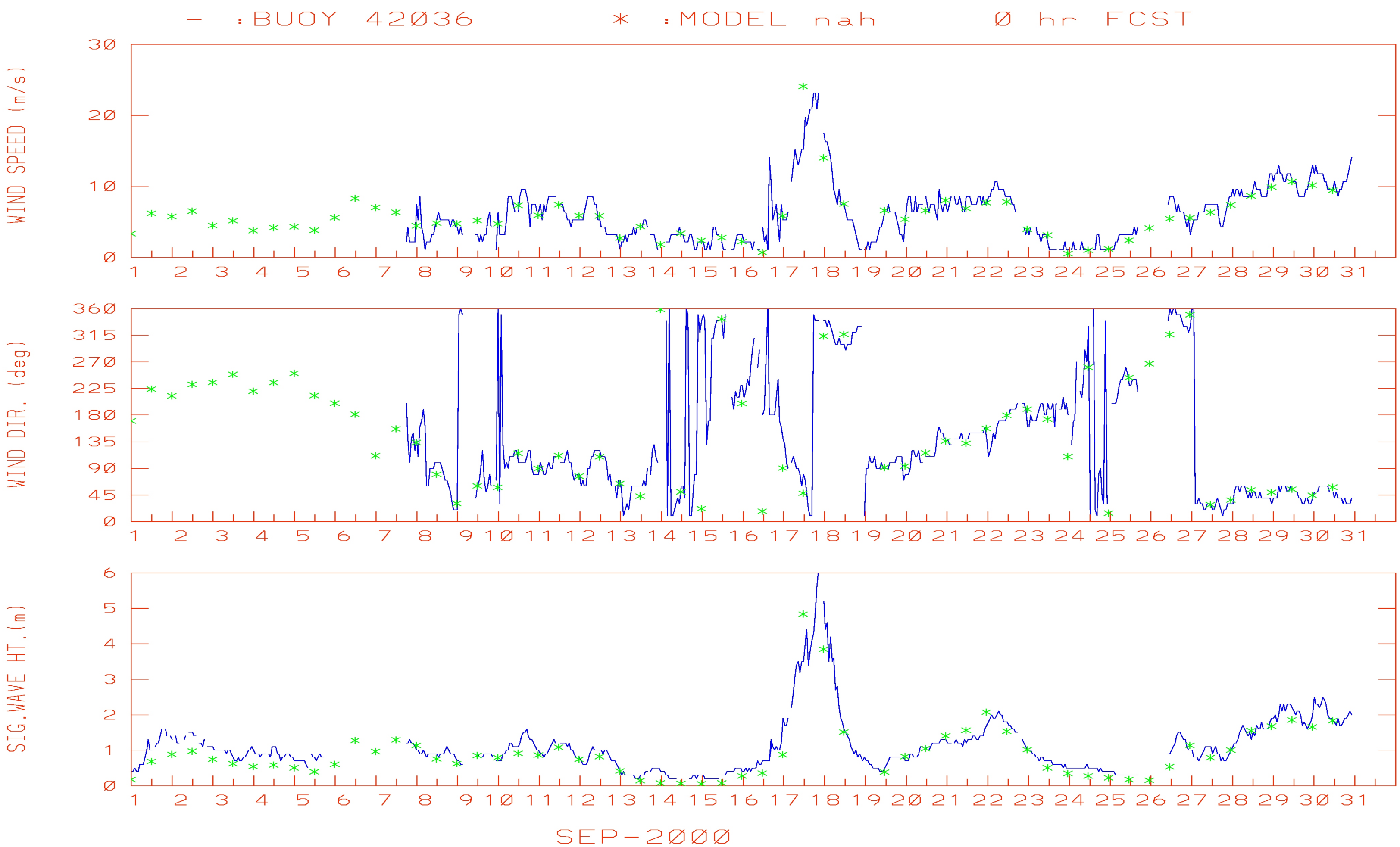

Figure 2a. Time series showing wind speed (top), wind direction (middle), and wave heights (bottom) for the month of September 2000 and comparing buoy data (blue line) from buoy 42036 with model output at 12-h intervals (green*). Wave height output is from the NAH, while wind output is a blend of GFS and GFDL wind output. Dates of interest are 16 - 25 September which contain peak values for Hurricanes Gordon and Helene, respectively.

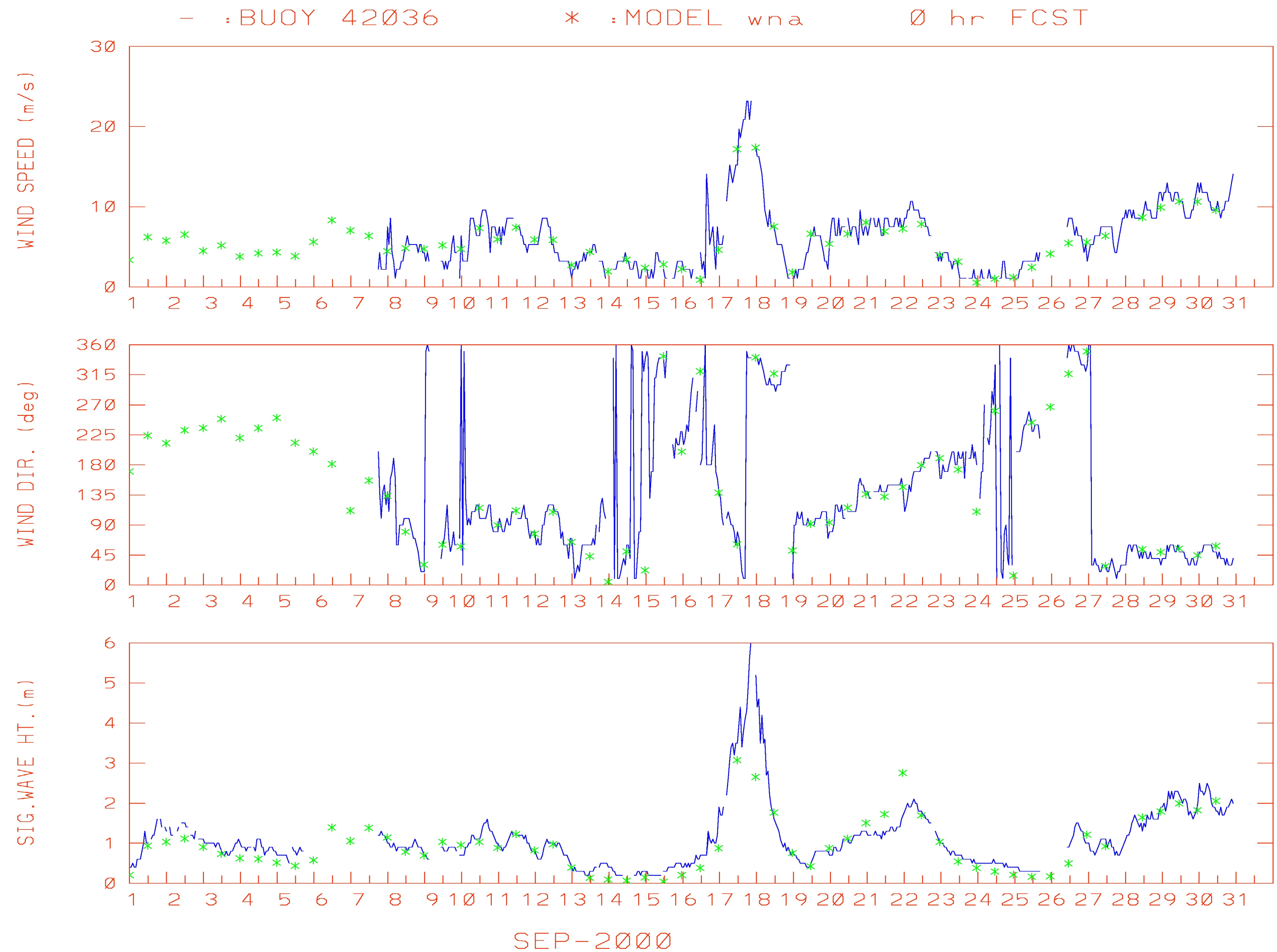

Figure 2b. Same as Fig. 2a except for WNA model and GFS winds only.

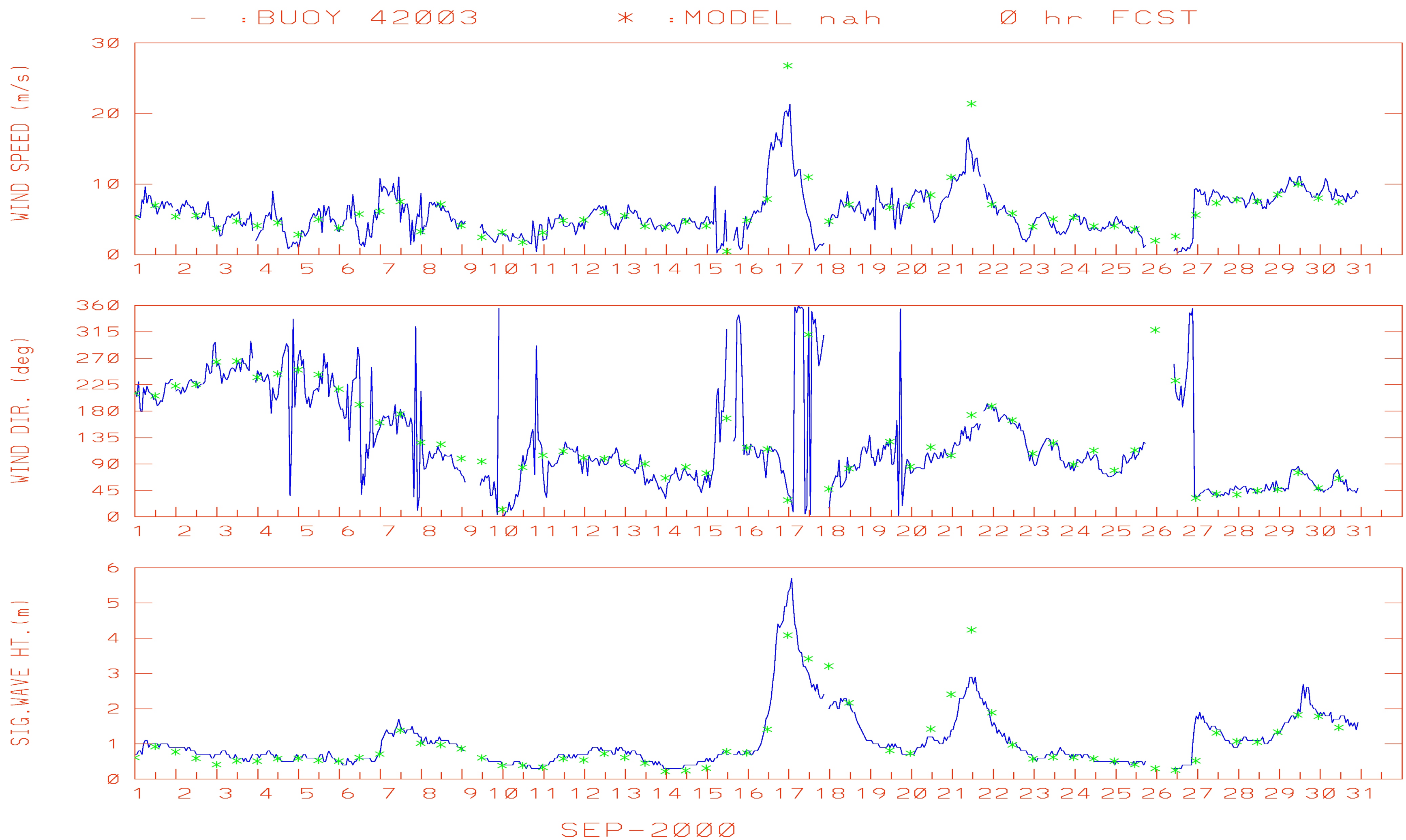

Figure 3a. Same as Fig. 2a except at buoy 42003.

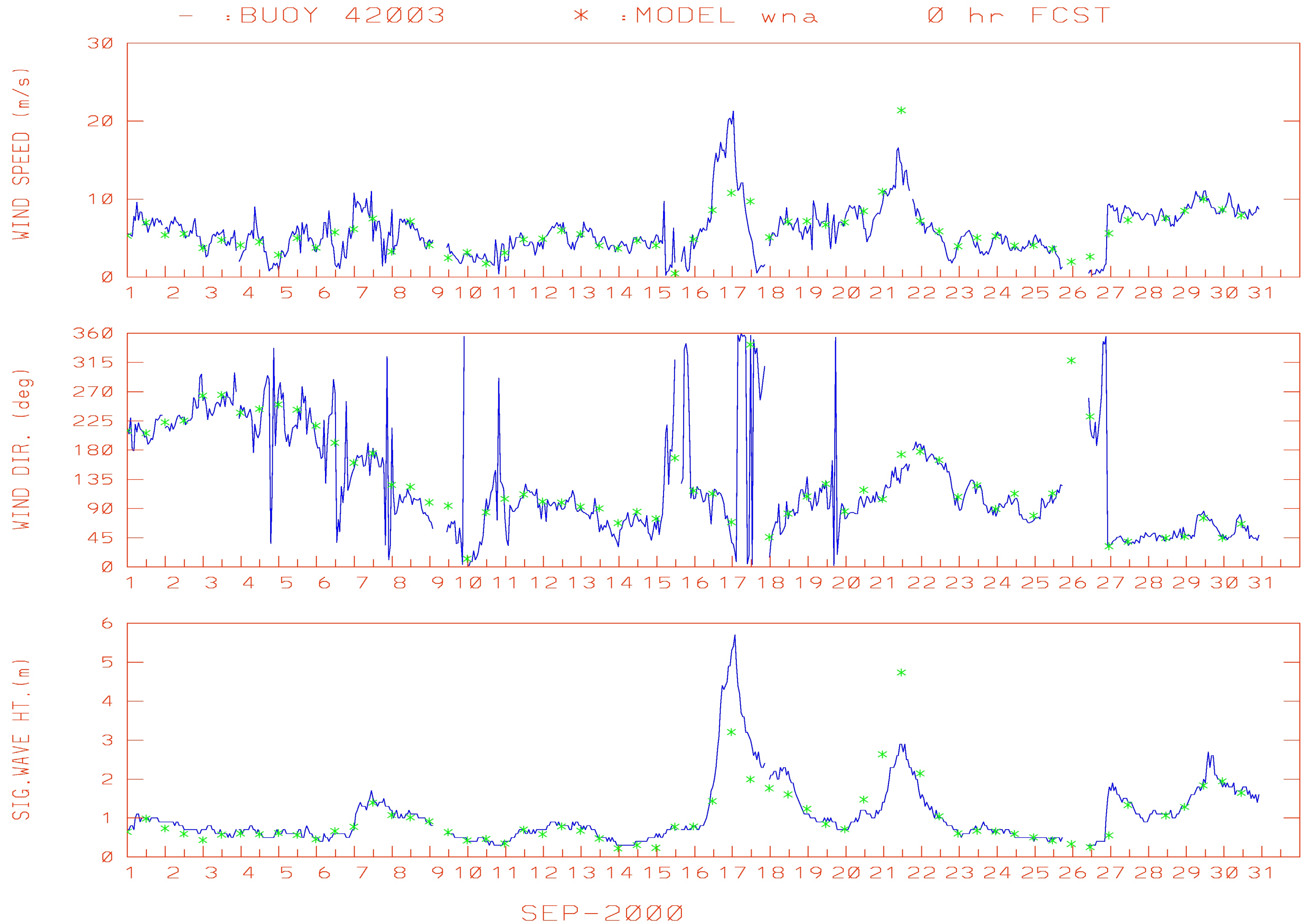

Figure 3b. Same as Fig. 2b except for buoy 42003.

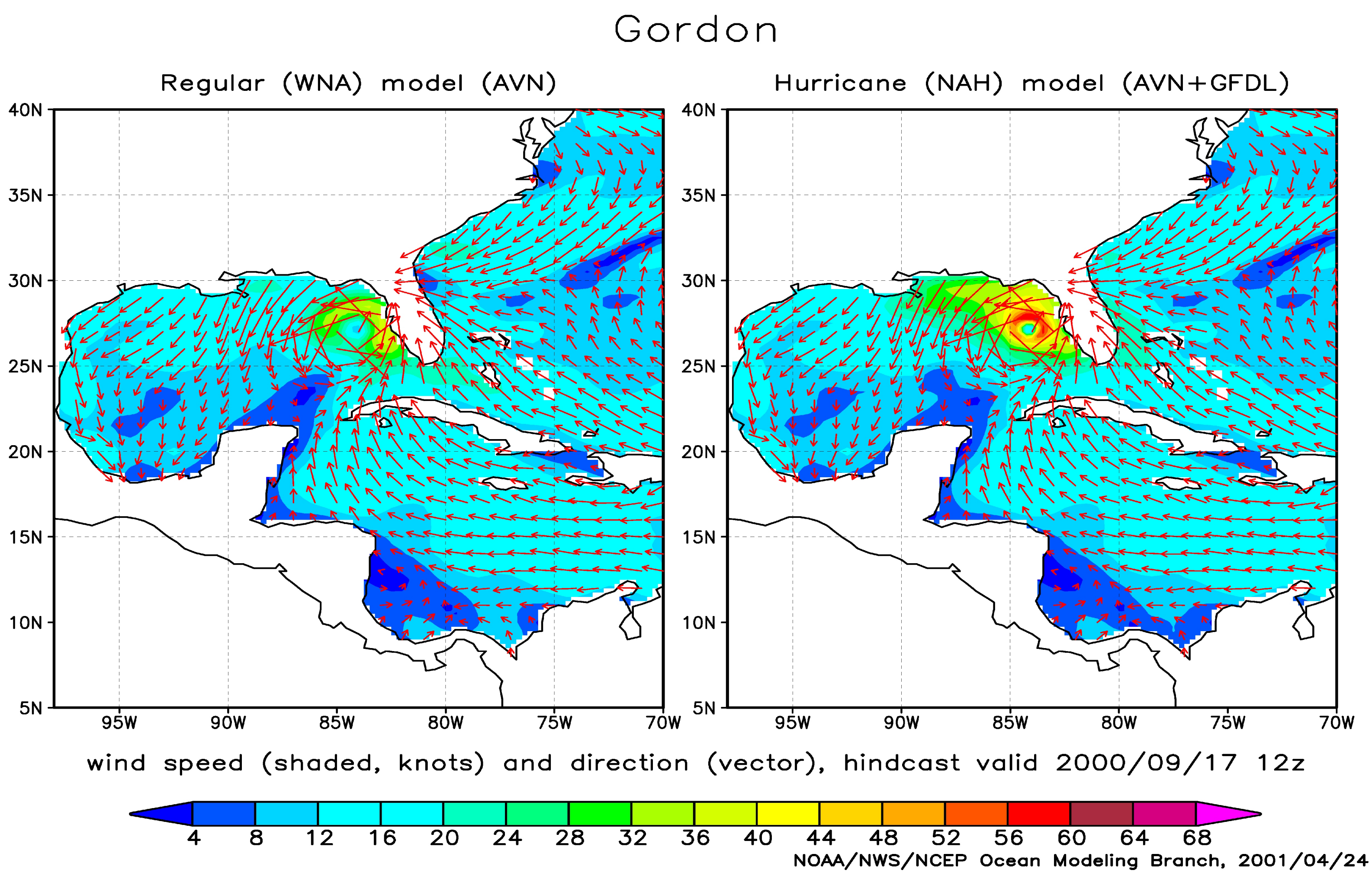

Figure 4a. Wind speed (shaded, knots) and direction (vector) for Hurricane Gordon. GFS wind field for WNA (left), and blended GFS and GFDL wind field for NAH (right).

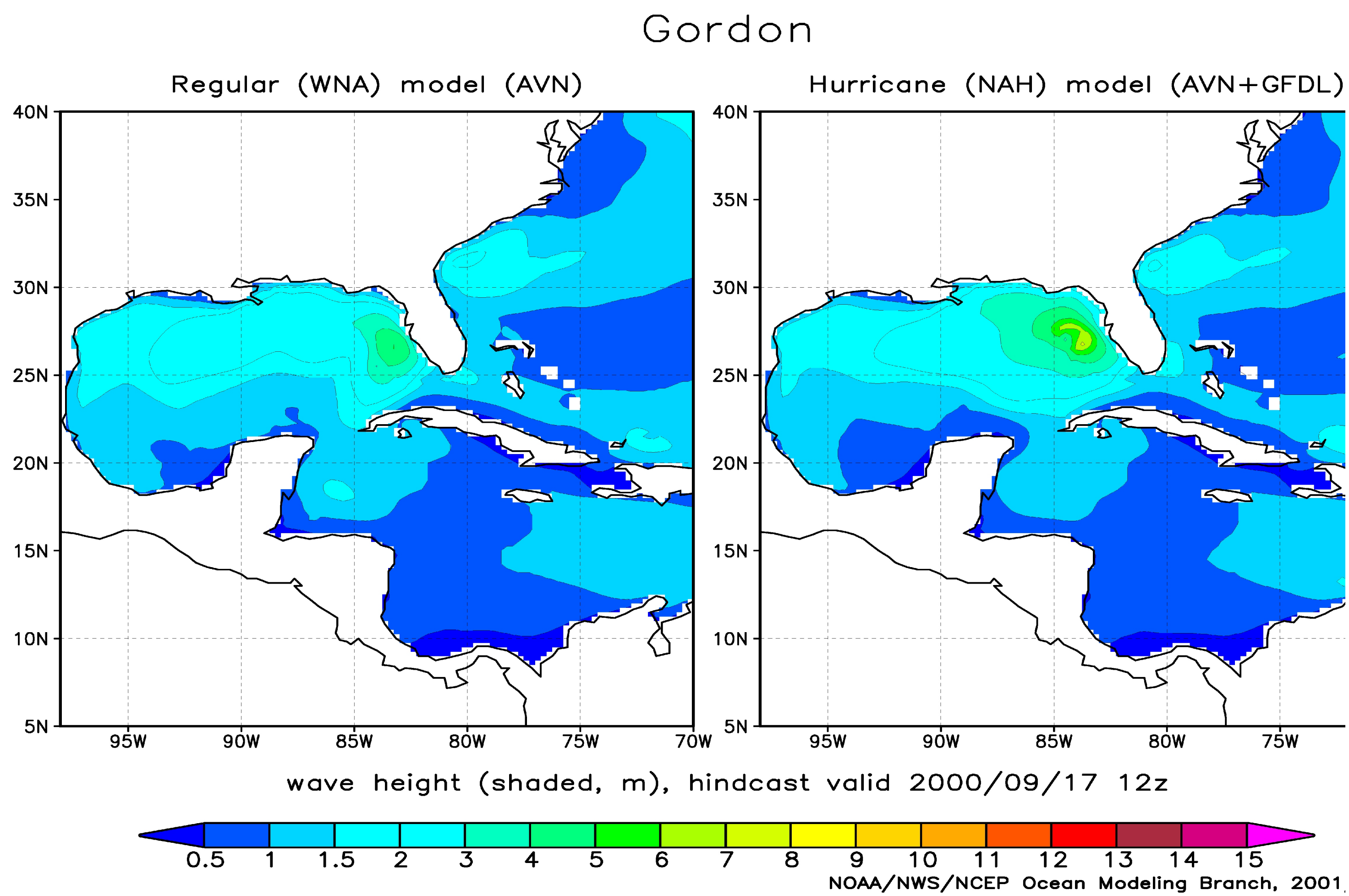

Figure 4b. Comparison of wave height fields (shaded, m) for Hurricane Gordon from WNA (left, GFS winds only) and NAH (right, blended GFS and GFDL winds). Figure 4a shows the corresponding wind fields.

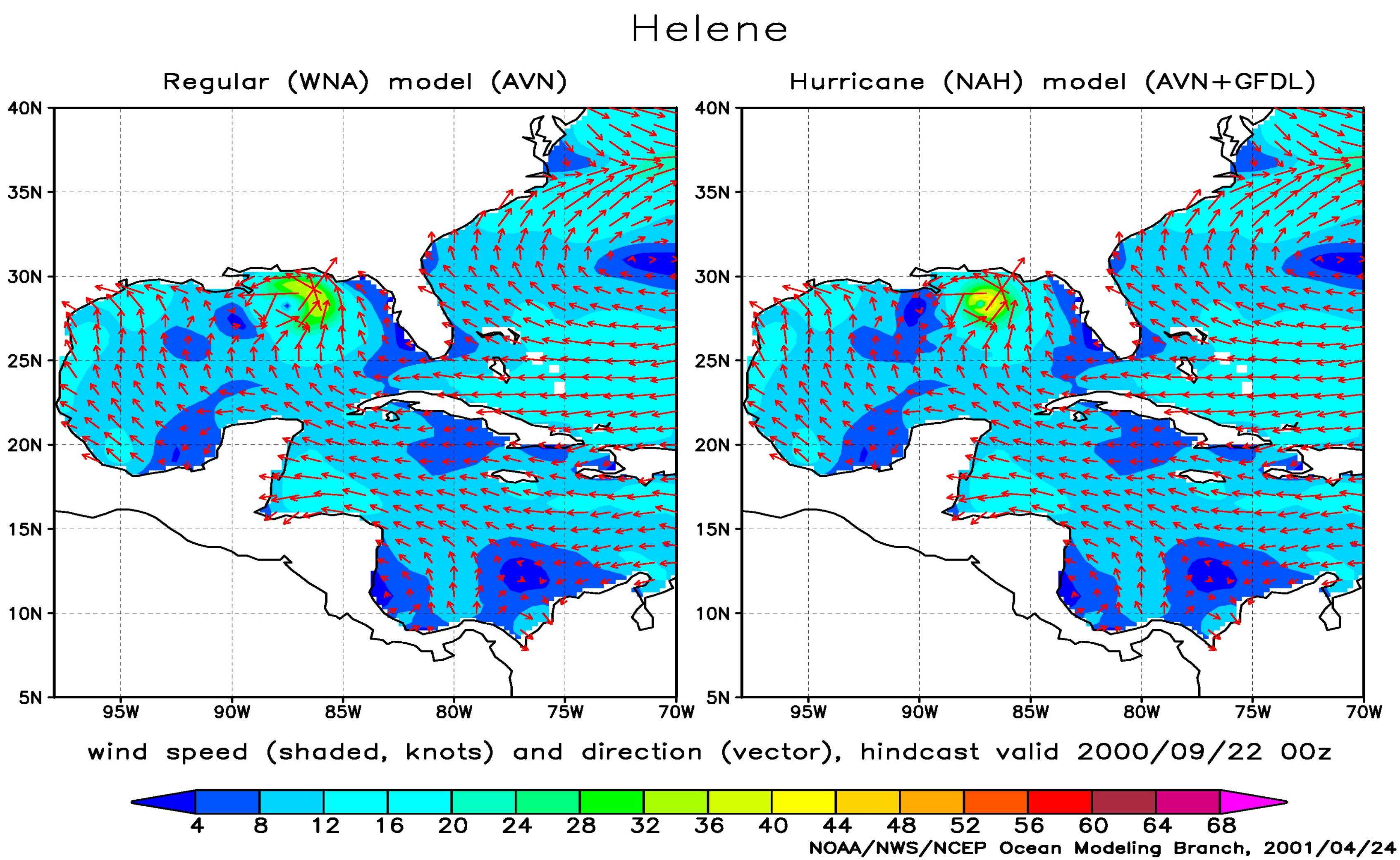

Figure 5a. Same as Fig. 4a except Hurricane Helen. Note the difference in wind fields: the GFS wind field (left) surrounding Helene is somewhat lower in intensity, but broader in extent then the same circulation with the blended winds from the GFS and GFDL (right).

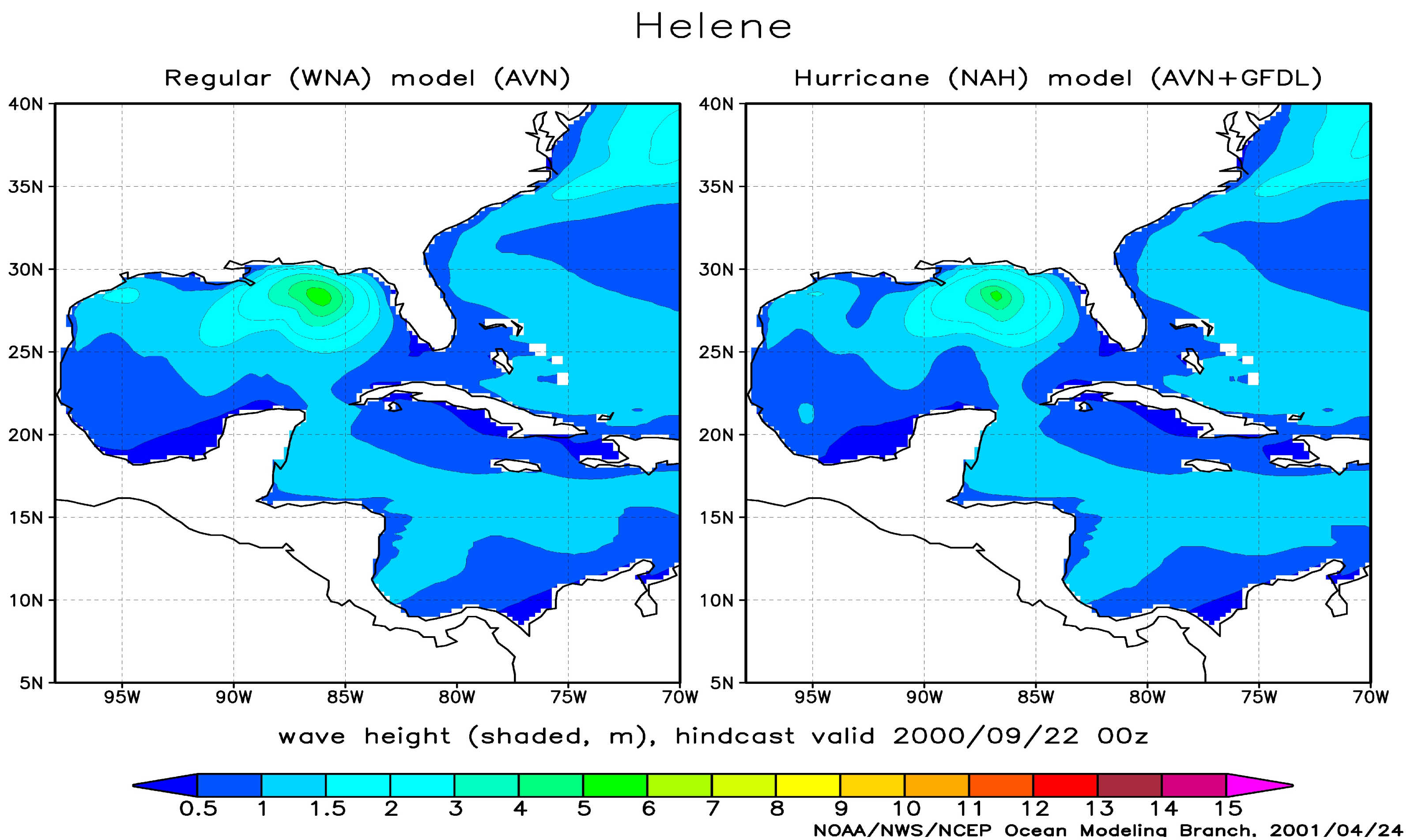

Figure 5b. Same as Fig. 4b except for Hurricane Helene. Note, the aerial extent of the wave field associated with the hurricane from the WNA (left) generated from GFS winds is larger than the wave field generated by the blended wind field from the NAH (right). The wave heights from the NAH are closer to those observed at buoy 42036 (Fig. 2a) than those from the WNA (Fig. 2b) and also to those observed at buoy 42003 (Figs. 3a and 3b).

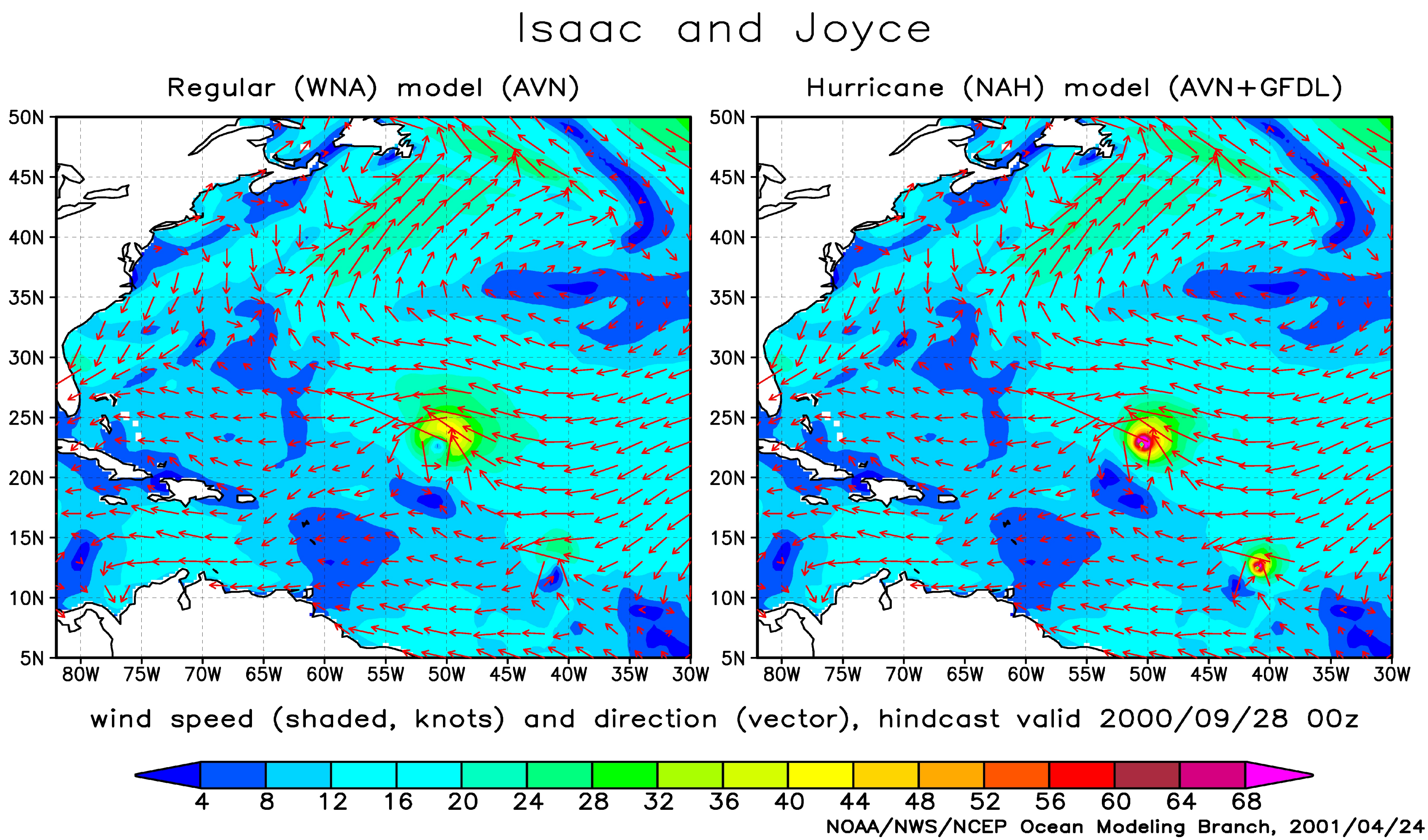

Figure 6a. Wind speed (shaded, knots) and direction (vector) comparing the wind fields for Hurricanes Isaac and Joyce from the GFS (left) with the GFS and GFDL blend (right). Note, the GFS hardly has any indication of Joyce and has less intensity and a more diffuse structure for Isaac than the blend.

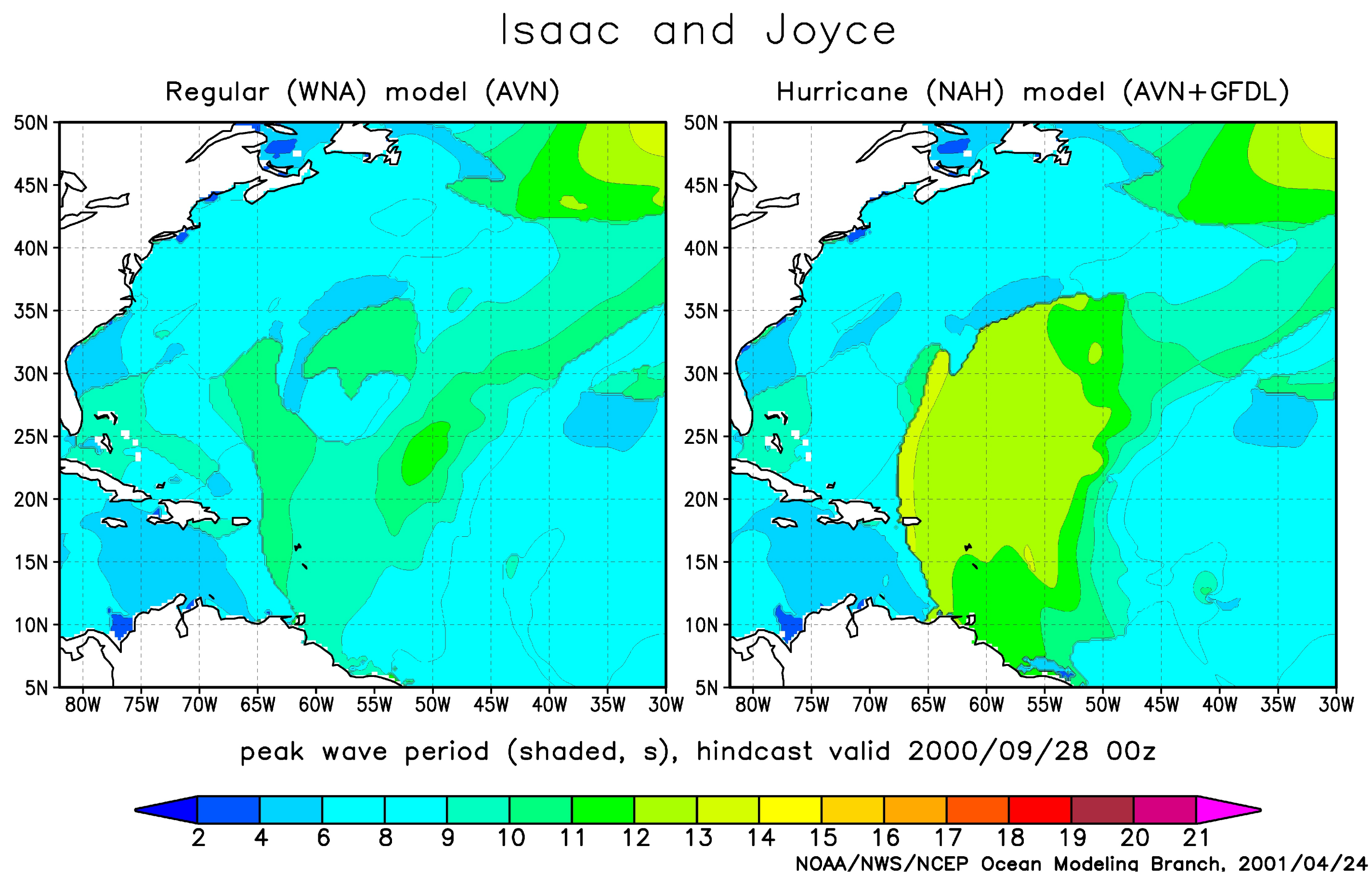

Figure 6b. Peak wave period (shaded, s) developed from GFS input to WNA (left) and GFS plus GFDL blended input to NAH (right). Note the difference between the two. The wave front generated by the NAH is 15 degrees to the West of where the storm centers are. As the storms continue West and then North, the wave front will continue westward and impact the East Coast of the U.S. without either hurricane ever coming near the coast. As depicted above the wave front contains waves with peak periods of 14 to 15 s which will give rise to very dangerous surf at the coast. In fact, 5 people died at the coast as a result of high surf generated by these hurricanes.

```
AGNT42 KWBJ 080428
OSBH03
LOCATION : 41002      (32.30N  75.20W)
MODEL    : NORTH ATLANTIC HURRICANE 0.25DEG
CYCLE    : 20020708 T00Z
<
DDHH HS SS PP DDD SS PP DDD SS PP DDD SS PP DDD SS PP DDD SS PP DDD
-------------------------------------------------------------------
0712  4  4 08 063  1 08 133
0713  4  4 08 064  1 08 134
0714  4  4 08 065  1 08 134
0715  4  4 08 065  1 08 134
0716  4  4 08 066  1 08 134
0717  4  4 08 067  1 08 134
0718  4  3 08 068  1 08 134
0719  4  3 08 068  1 08 134
0720  4  3 08 069  1 08 135
0721  3  3 08 069  1 08 135  1 02 188
0722  3  3 08 070  1 08 134            1 02 206
0723  3  3 08 071  1 08 134            1 02 213
0800  3  3 08 071  1 08 134            1 02 211
0801  3  3 08 072  1 08 134            1 02 212
0802  3  3 08 072  1 08 134            1 02 213
0803  3  3 08 073  1 08 135  0 03 235  1 02 214
0804  3  3 08 074  1 08 134  1 03 235  1 02 212
0805  4  3 08 074  1 08 134            2 02 225
0806  4  3 08 074  1 08 134            2 03 219
0807  4  3 08 075  1 08 133            2 03 219
0808  4  2 08 075  1 08 133            2 03 221
0809  4  2 08 076  1 08 134            2 03 224
0810  4  2 08 077  1 08 134            2 04 228
0811  4  2 08 077  1 08 133            2 04 231
0812  3  2 08 078  1 08 133            2 04 232
0813  3  2 08 077  1 08 132            2 04 233
0814  3  2 08 078  1 09 133            2 04 235
0815  3  2 08 078  1 09 133  1 07 132  2 04 235
0816  3  2 09 078            1 08 131  2 04 236
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0818  3  2 08 093  1 05 273            2 04 232
0819  3  2 09 093  1 05 273            2 04 234
0820  3  2 09 093  1 05 274            2 04 235
0821  3  2 09 093  1 05 275            2 04 236
0822  3  2 09 093                      2 04 246
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0900  3  2 09 092                      2 04 249
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0902  3  2 09 092                      2 04 253
0903  3            2 08 073  2 09 116  2 05 255
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0906  3            2 08 073  2 09 115  2 05 255
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0909  3  2 05 270  2 08 073  2 09 115            1 03 216
0910  3  2 04 270  2 08 073  2 09 114            1 03 216
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0911	3	2 04 269	2 08 074	2 09 114		1 04 215
0912	3	2 04 269	2 08 074	2 09 114		1 04 215
0913	3	2 04 268	2 08 074	2 08 114		1 04 215
0914	3	2 04 266	2 08 074	2 08 114		1 04 213
0915	3	1 04 267	2 08 074	1 08 114		1 04 214
0916	3	1 04 267	1 08 074	1 08 114		1 03 214
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0918	3	1 04 266	1 08 074	1 08 114		2 03 213
0919	3	1 04 266	1 08 074	1 08 114		2 03 215
0920	3	1 04 267	1 08 074	1 08 114		2 03 215
0921	3	1 04 266	1 08 074	1 08 114		2 03 215
0922	3	2 04 255	1 08 074	1 08 114		1 03 202
0923	3	2 04 263	1 09 074	1 08 114		2 04 212
1000	3	2 05 263	1 09 074	1 08 114		2 04 212
1001	3	2 05 263	1 09 073	1 08 114		2 04 212
1002	3	2 05 263	1 09 073	1 08 114		2 04 212
1003	3	2 05 263	2 09 073	1 08 114		2 04 212
1004	3	2 05 264	2 09 073	1 08 114		2 04 211
1005	3	2 05 264	2 09 072	1 08 114		2 04 209
1006	3	2 05 264	2 10 072	1 08 114		2 04 208
1007	4	2 05 264	2 10 072	1 08 114		2 04 209
1008	4	2 05 264	2 10 072	1 08 115	0 07 020	2 04 208
1009	4	2 05 260	2 10 072	1 08 115	1 07 022	2 04 206
1010	4	2 05 255	2 10 072	1 08 115	1 07 023	2 04 197
1011	4	2 05 254	2 10 071	1 08 115	1 07 024	2 04 196
1012	4	2 05 255	2 10 071	1 08 115	1 07 024	2 04 196
1013	4	2 05 255	2 09 071	1 08 115	1 07 025	2 04 198
1014	3	2 05 255	2 09 071	1 08 115	1 07 025	2 04 198
1015	3	2 05 254	2 09 071	1 08 115		2 04 196
1016	3	2 05 256	2 09 071	1 08 116		2 04 197
1017	3	2 05 257	2 09 070	1 08 116		2 04 201
1018	3	2 05 257	2 09 070	1 08 116		2 04 200
1019	3	2 05 257	2 09 070	1 08 116		2 04 199
1020	3	1 05 260	2 09 070	1 08 116		2 04 203
1021	3	1 06 271	2 09 070	1 08 116		2 04 203
1022	3	1 06 270	2 09 070	1 08 116	1 05 251	2 04 203
1023	3	1 06 269	2 09 070	1 08 116	1 05 247	2 04 196
1100	3		2 09 069	1 08 116	2 05 252	2 04 195

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DD  = DAY OF MONTH
HH  = HOUR OF DAY
HS  = TOTAL SIGNIFICANT WAVE HEIGHT (FEET)
SS  = SIGNIFICANT WAVE HEIGHT OF SEPARATE SYSTEM (FEET)
PP  = PEAK PERIOD OF SEPARATE SYSTEM (WHOLE SECONDS)
DDD = MEAN DIRECTION OF SEPARATE SYSTEM (DEGREES/"FROM")
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Figure 7. Sample Spectral Wave Bulletin for buoy 41002 from the NAH wave model. Values are for a 12-h hindcast and a 78-h forecast with hourly values. The last 6-h are not depicted here.